# REACTION OF THE WALL OF AN ENTRANCE CAVITY AGAINST THE AFTERBODY OF A PROJECTILE

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# REACTION OF THE WALL OF AN ENTRANCE CAVITY AGAINST THE AFTERBODY OF A PROJECTILE

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CONTENTS

## ABSTRACT

The cavity phase of the water entry of a projectile is described and the results are presented for the beginning of an experimental investigation of the hydrodynamic forces that affect projectile motion within a cavity. Lift-force measurements were made on two afterbody shapes that were supported so that they dug into the surface of a flowing stream of water. The similarity between these tests of models in the Free-Surface Water Tunnel and operating conditions of a full-scale projectile is discussed.

# REACTION OF THE WALL OF AN ENTRANCE CAVITY AGAINST THE AFTERBODY OF A PROJECTILE

An analysis of the water entry of a projectile shows that the hydrodynamic forces affecting the motion act separately on the nose and afterbody during the cavity phase. Investigations of entry are usually done by simulating the hydrodynamic phenomena as a whole for some specific projectile shape and measuring the resulting motion or over-all forces. There are advantages, however, (especially as an aid in determining or improving a basic projectile design) in making separate measurements of the forces on various nose and afterbody shapes under flow conditions similar to those encountered in a cavity. These neasurements can then be used to determine the over-all hydrodynamic conditions that affect the motion for any desired combination of nose, afterbody, and projectile length. Separation of the two effects produces information of a more basic nature since this allows the data to be combined for a large variety of projectile designs and conditions of flow.

The results of the first measurements of lift forces on two afterbody shapes are given below since there is very little information on the reaction of a cavity wall against an afterbody. Additional tests are necessary, however, since lift alone does not fully determine the hydrodynamic forces on the model and since the test conditions have not yet been varied to show the extent to which such measurements can be used to predict full-scale operation. These conditions governing the similarity between model tests and prototype operation are discussed at the end of this report.

## The Cavity Phase of the Water Entry of a Projectile

When a projectile enters a body of water from above the surface, it generally opens up a cavity larger than its diameter. It may then proceed along its course with only its nose in contact with the water. It is unlikely that the projectile will continue to proceed in this attitude for a large portion of the cavity phase of its travel since the equilibrium is unstable for the usual nose shapes.

A slight departure from the position of equilibrium in which the projectile is riding down the center of the cavity will cause the hydrodynamic forces on the nose to produce an overturning moment which rotates the projectile further and brings its afterbody in contact with the cavity wall. With sufficient penetration of the afterbody through the interface of the cavity, the hydrodynamic forces on this part of the projectile may reach a value sufficient to counteract the overturning moment produced by the forces on the nose. If further rotation causes the righting moment to become predominant, stable running may be established at this equilibrium condition with the afterbody, as well as the nose, in contact with the water.

During the cavity phase of water entry, the equilibrium condition described above may cause two separate and distinct regions of the projectile to be in contact with the water. The contact at the nose opens up the cavity by causing the water to be deflected clear of the surface of the projectile. Then, with some misalignment of the projectile within the cavity, the afterbody also contacts the water at the wall of the cavity that was produced by the nose. Between these two regions of contact at the nose and afterbody, there may be a portion of the surface of the projectile with little or no contact. Since the hydrodynamic forces act only on the regions of contact with the water, the forces on these regions can be investigated separately. Tests have been started first on the afterbody section of the projectile since very little can be deduced analytically for the complicated shapes involved.

Cavity Investigations in the Free-Surface Water Tunnel

The Free-Surface Water Tunnel provides a flowing stream that can be used to subject a model to the hydrodynamic forces due to the relative motion between the fluid and the model. Since this tunnel provides a test channel with an air-water interface, it can be used for tests on models of craft that operate at or near a water surface. During the cavity phase of the water entry of a projectile, the surface of the water affects the motion while initial penetration and shallow running are taking place; furthermore, throughout the cavity phase, an interface is carried along with the projectile. These various stages of the cavity phase are similar to those that can be obtained by supporting models in the Free-Surface Water Tunnel.

Before starting a systematic study of simple, geometric shapes as components of afterbodies, one of the existing models of the Mark 13-6 Torpedo with ring tail was used to explore the methods of using the tunnel and associated equipment for cavity investigations. It is important to determine what procedures provide hydrodynamic conditions around the model that are adequately similar to the operating conditions of projectiles of a different size. These first tests can be considered only the beginning of such an exploration of the possibilities of the Free-Surface Water Tunnel.

Lift Force on the Afterbody of the Mark 13-6 Torpedo

Steady-state conditions simulating various cavity configurations can be produced by supporting models in a flowing stream. Figure 1 is a view looking through the transparent walls of the tunnel where a cavity is seen surrounding a model of the Mark 13-6 Torpedo. Since the only contact with the water is at the nose, the torpedo in free flight would be unstable and would not remain in this orientation in the cavity. The overturning moment would rotate the projectile and cause the afterbody to intersect the wall of the cavity. After such rotation, the submergence of the tail structure through the interface of the cavity might produce conditions similar to those shown in Figures 2 and 3.

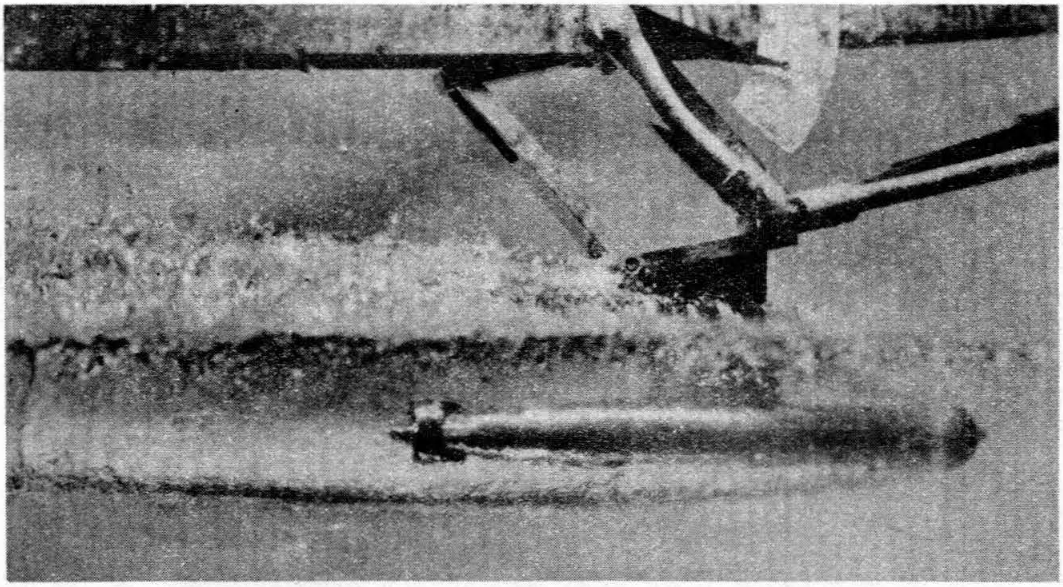

FIG. 1 – ENTRY-CAVITY CONDITIONS CAN BE SIMULATED IN THE FREE-SURFACE WATER TUNNEL. THIS PHOTOGRAPH SHOWS A MODEL OF THE MARK 13-6 TORPEDO "RIDING ON ITS NOSE" INSIDE A CAVITY.

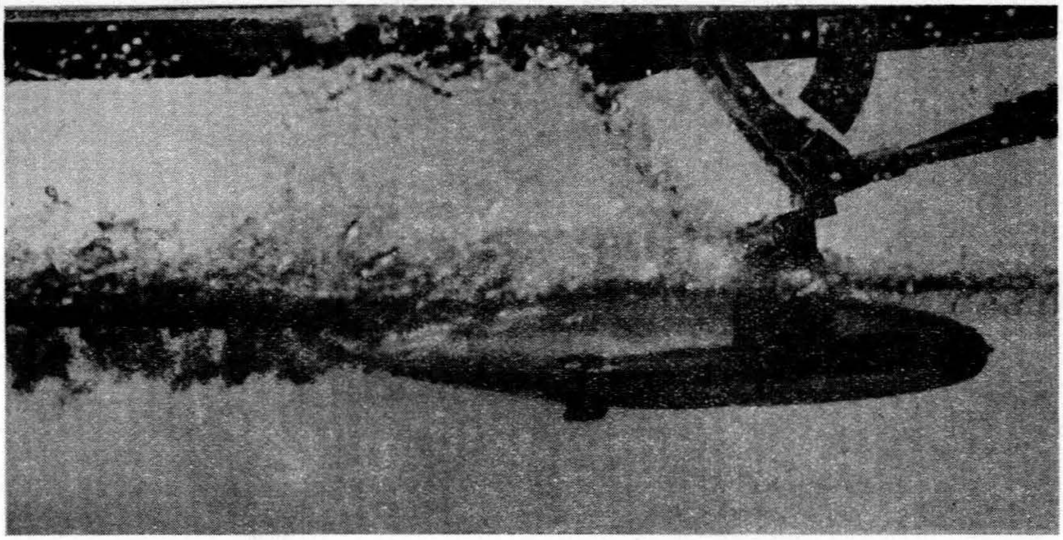

FIG. 2 – THE CAVITY AT A LATER STAGE OF COLLAPSE THAN THAT SHOWN IN FIGURE 1. THE TORPEDO HAS A SLIGHT UPWARD PITCH AND THE AFTERBODY IS BEGINNING TO BE SUBMERGED THROUGH THE INTERFACE

The angle of attack and the submergence of the tail structure through the interface have been used as variable parameters in presenting the results of measurements of the hydrodynamic forces on afterbody structures. The first tests used the flat water surface in the Free-Surface Water Tunnel as an approximation of the cavity interface. The lift force on the afterbody was measured first because it produces the major portion of the righting moment on the projectile for any reasonable angle of attack. A simple one-component balance mounted above the water surface was consequently adequate for these preliminary tests. The details of the test arrangement are given in the appendix. For complete data on afterbody forces, nose forces, and forces on assembled projectiles, a three-component balance that measures drag, lift, and pitching moment is under construction.

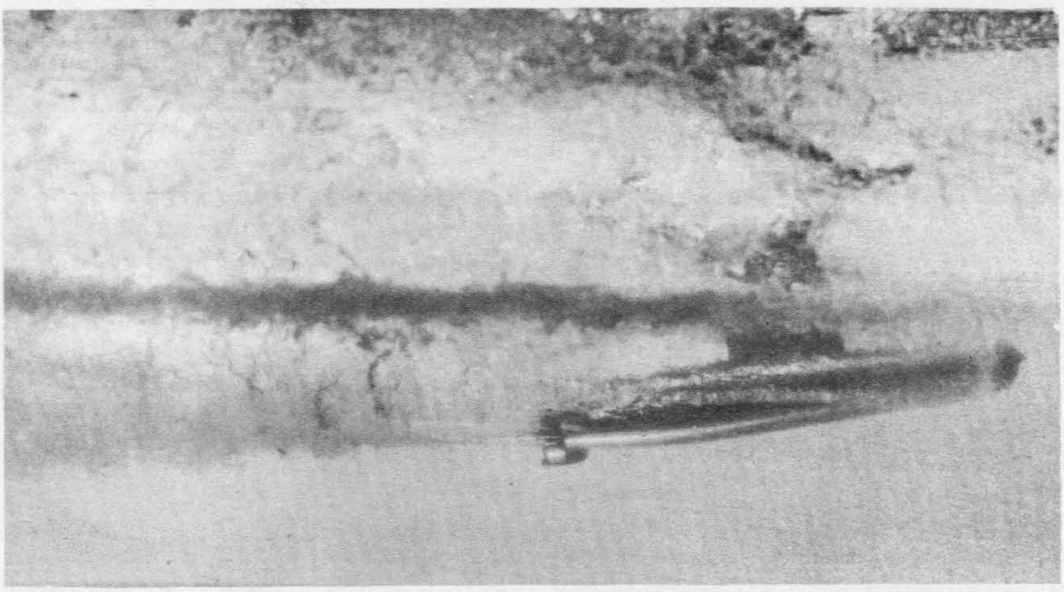

FIG. 3 — A LARGER PITCH ANGLE CAUSES GREATER SUBMERGENCE OF THE AFTERBODY. THE HYDRODYNAMIC FORCES ON THE NOSE AND THE AFTERBODY PRODUCE OPPOSING MOMENTS ABOUT THE CG OF THE PROJECTILE. A STABILIZING EFFECT CAN BE OBTAINED ONLY IF THE INCREASING SUBMERGENCE AND ANGLE OF ATTACK OF THE AFTERBODY CAN PRODUCE A MOMENT THAT EXCEEDS THE OVERTURNING MOMENT DUE TO THE NOSE FORCES.

The results of the tests on the Mark 13-6 Torpedo with ring tail are given in Figure 4 as a lift coefficient* plotted against the submergence of the rearmost center point of the afterbody.

*The lift coefficient is here defined as $C_L = \dfrac{L}{\rho \frac{V^2}{2} A_D}$ , where $L$ is the lift force in pounds including buoyancy, $\rho$ is the density of the water in slugs per cubic foot, $V$ is the velocity in feet per second, and $A_D$ is the cross-sectional area of the projectile at its major diameter in square feet.

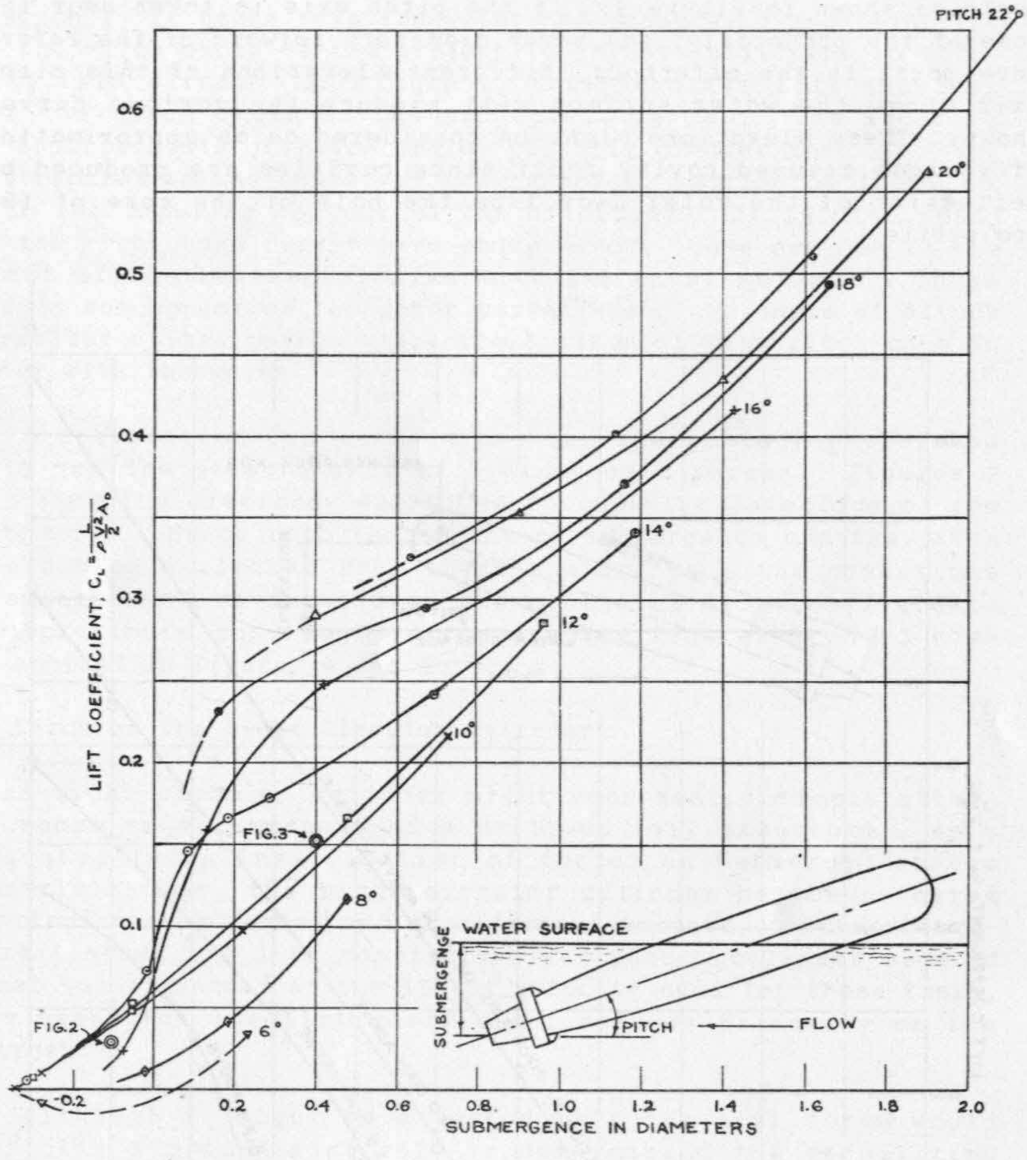


FIG. 4 - LIFT COEFFICIENT VS. SUBMERGENCE FOR A 2-IN. DIAM. MODEL OF THE MARK 13-6 TORPEDO. FLOW VELOCITY 15 FPS.

More information is provided on the behavior of the torpedo as it pivots within the cavity by plotting lift coefficient vs. pitch angle as shown in Figure 5. If the pitch axis is taken near the nose of the projectile, say seven diameters forward of the reference point in the afterbody, different elevations of this pitch axis above the water surface will produce the various curves shown. These elevations might be considered as an approximation of various assumed cavity radii since cavities are produced by deflection of the water away from the path of the nose of the projectile.

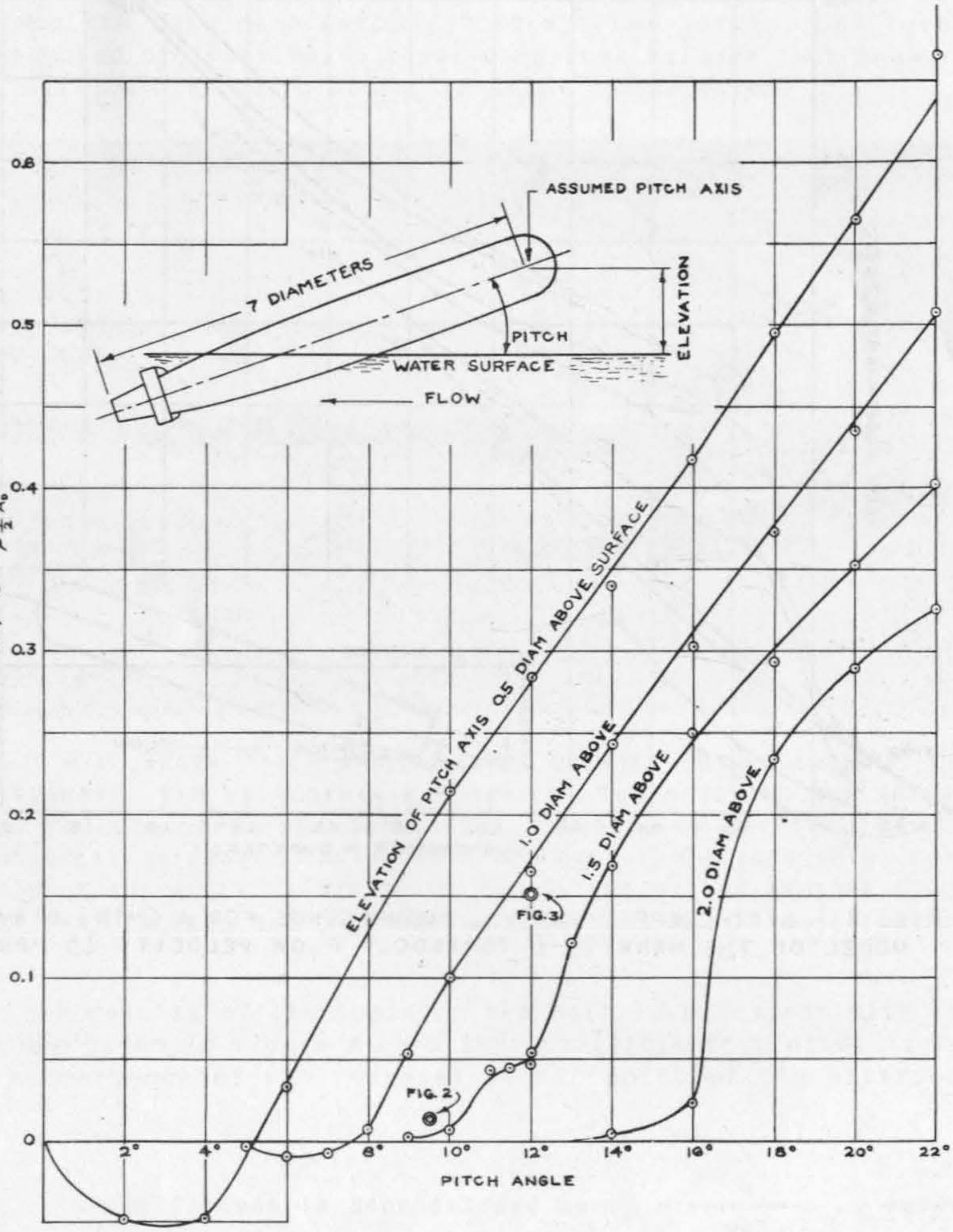


FIG. 5 – LIFT COEFFICIENT VS. PITCH ANGLE FOR A 2-IN. DIAM. MODEL OF THE MARK 13-6 TORPEDO. FLOW VELOCITY 15 FPS.

The shroud ring of the Mark 13-6 Torpedo is conical with a half angle of 4°. The ring tilts outward at the leading edge; consequently it hooks into the water and produces a negative lift when the pitch angle of the projectile is not sufficient to counteract this effect. In Figure 5, this negative lift shows up where the pitch angle of the projectile is low. The negative lift that persists at pitch angles slightly greater than 4° might be attributed to the camber of the hydrofoil section of the ring and to the tapering contour of the afterbody. It is also noted that the right-hand curves have sharp bends; these are due to the contact of the horizontal fins with the water surface. These bends do not appear on the other curves where the angle of attack was smaller at the points where the horizontal fins first came in contact with the water.

A correlation can be made between the photographs of the cavity and the measurements of hydrodynamic forces. Figures 2 and 3 show the afterbody submerged through the interface of the cavity wall. Since both the amount of submergence and the pitch angle can be estimated from these photographs, the conditions represented can be located on the graphs of lift coefficient. The approximate positions represented by Figures 2 and 3 have been spotted in Figures 4 and 5.

## Lift Force on the Right Circular Cylinder

A right circular cylinder might represent a simple afterbody shape or a component of a built-up tail structure. As a first step in an investigation of forces on submerged simple geometric shapes, the right circular cylinder has been tested at various attack angles and at different amounts of submergence. Figure 6 shows the lift coefficient for such a cylinder plotted against submergence. At the 15-fps velocity used for these tests, it is seen that the lift coefficient depends primarily on the submergence.

Although it might be expected that the lift force would often play a predominant role in determining the stabilizing moment on a projectile, it should be realized that these tests are incomplete without additional components in the measurements. Drag and pitching-moment measurements will also be required to determine completely the hydrodynamic forces. These three components: drag, lift, and pitching moment, constitute a complete set of measurements when the model is symmetrical about the drag-lift plane.

## Similitude for Flow Phenomena near an Interface

Further investigation is required to fully determine the range of prototype operating conditions that can be investigated by means of model tests in the Free-Surface Water Tunnel. This range is determined primarily by the requirement that the inertial and gravitational effects about the modeland prototype be similar. It is further limited, however, by the extent and method of evaluating the resulting dissimilitude for viscous and surface-tension

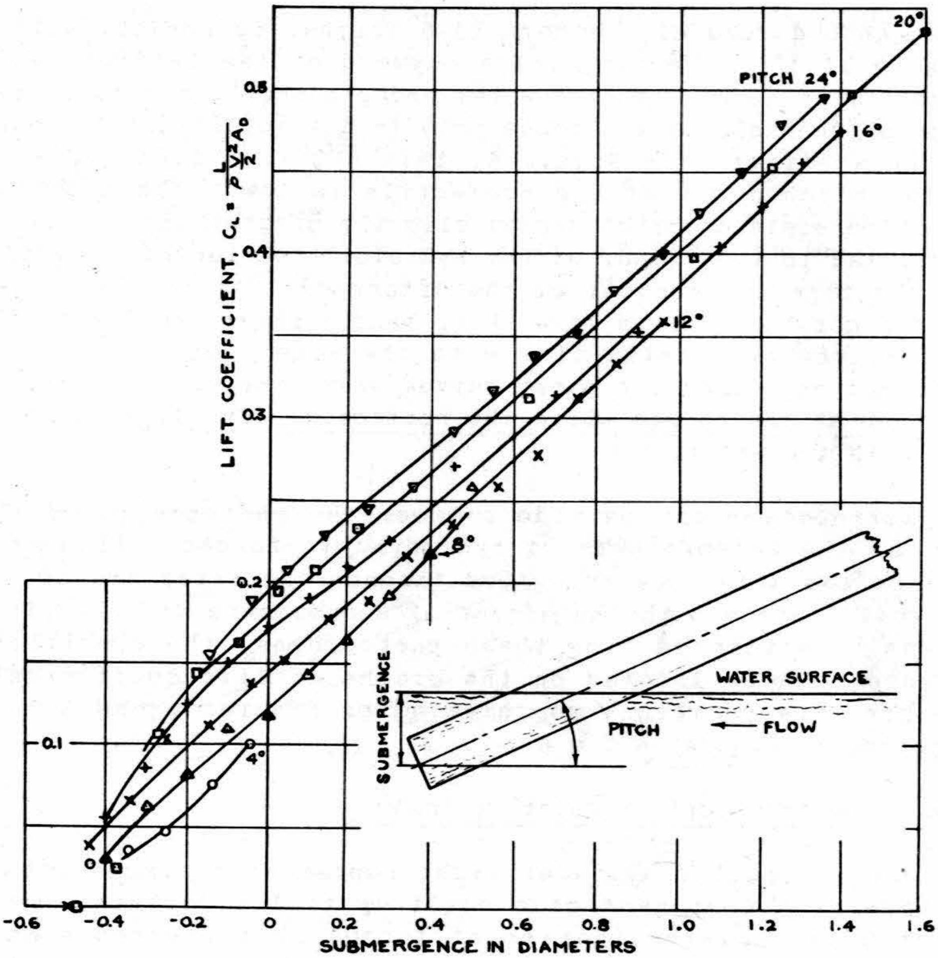


FIG. 6 – LIFT COEFFICIENT VS. SUBMERGENCE FOR A 2-IN. DIAM. RIGHT CIRCULAR CYLINDER. FLOW VELOCITY 15 FPS

effects. For entrance-cavity investigations, the similarity between the test conditions using a flat water surface and the operating conditions where the afterbody intersects the curved interface of the cavity behind the nose of the projectile should be scrutinized. Predictions from flat-surface tests can be checked against tests of models operating inside a cavity, when a three-component balance is installed since it will permit measurement of hydrodynamic forces on projectiles and their components under conditions similar to those shown in Figures 1, 2, and 3. A study is also required to determine the extent to which the steady-state test conditions can represent, with adequate similarity, the cavity shapes and the flow patterns produced by a projectile that is decelerating and changing in orientation.

Although the flow velocity and model size is constant for the part of the tests covered by this preliminary report, these conditions require variation since such changes affect the ratio of inertial to gravitational forces acting on the model. This ratio, the Froude number for the flow conditions, governs the action of hydrodynamic forces where an interface between fluids of different specific gravity is involved. Strict inertial-to-gravitational similitude between model tests and prototype operation would require the Froude numbers to be identical. This identity is accomplished, when relative motion of only one of the fluids is significant, by making the ratio $\frac{\rho V^2/\ell}{\Delta\gamma}$* the same for model and prototype. The velocity limitation of the tunnel does not permit strict Froude number similitude to be maintained for values as high as those that might be encountered during the water entry of a projectile. Exact equality of the Froude numbers is not necessary, however, when the unit inertial forces $(\rho V^2/\ell)$ are predominant in both cases. Tests at other Froude numbers are required to determine how the hydrodynamic force coefficients are affected when the gravitational influence due to $\Delta\gamma$ becomes significant.

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*In this form, where $V$ is the significant relative velocity of flow, $\rho$ is the density of the flowing fluid, $\ell$ is a characteristic length, and $\Delta\gamma$ is the difference in the specific weights of the two fluids, the Froude number is the ratio of the unit inertial to the unit gravitational force. The square root of this quantity gives the Froude number in the form $\frac{V}{\sqrt{\ell\Delta\gamma/\rho}}$. When the relative motion involves water, with air across the interface, $\Delta\gamma$ is almost equal to the specific weight, $\gamma$, of water. Then, since $\gamma/\rho$ is equal to the gravitational acceleration, $g$, the Froude number reduces to

$$F = \frac{V}{\sqrt{g\ell}}$$

## APPENDIX

### The Measurement of Lift Force

As illustrated in Figures 7 and 8, the model was mounted on one end of a long beam which acted as a balance for measuring the hydrodynamic lift force. The other end of the beam was attached to the working section of the Free-Surface Water Tunnel by means of a flexure hinge which provided a horizontal pivot axis. By applying weights to the beam and adjusting a flexible spring counterbalance, the angular position of the beam about the horizontal axis of the flexure hinge was set to give some desired value on an elevation index before the water was brought up in contact with the model. After the flowing stream was brought up so that the model intersected the interface, additional weights were applied to the beam in order to bring the elevation index back to its former value. This weight increment, the horizontal distance from the weights to the pivot, and the horizontal distance from the pivot to the estimated center of lift on the model were then used to calculate the magnitude of the lift force. Measurements were made at different elevations and pitch angles in order to obtain the points plotted on the graphs in Figures 4, 5, and 6.

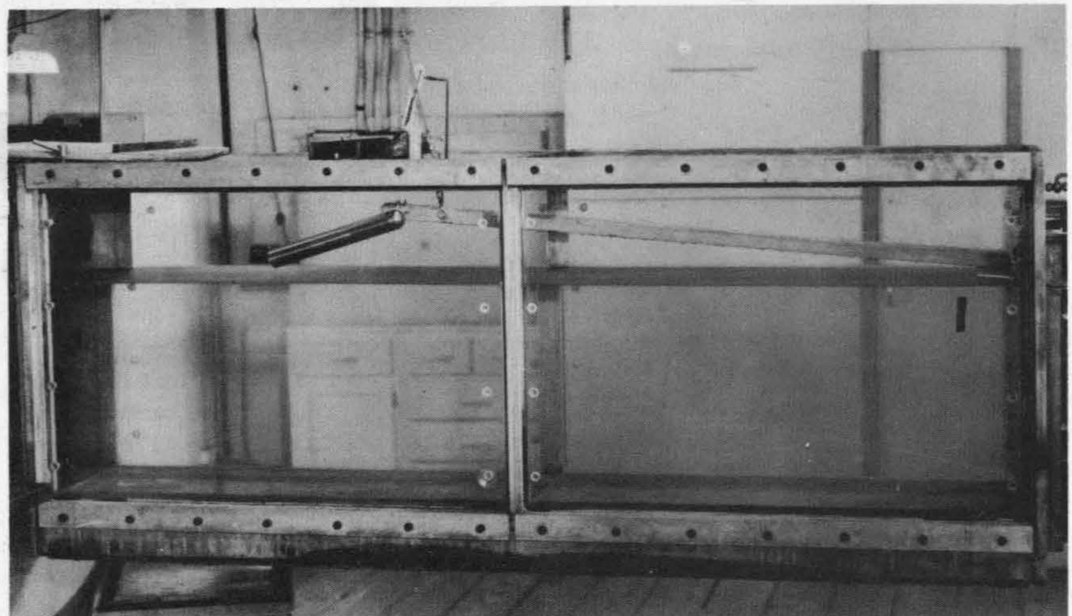

FIG. 7 — THE WORKING SECTION OF THE FREE-SURFACE WATER TUNNEL WITH A MODEL SUPPORT ARRANGED FOR MEASURING LIFT FORCE.

The measurements have neglected the effect of the drag force on the rotation of the beam. This would be small, however, because the pivot axis position was about 6 feet upstream from the rear end of the model and only 1/2 inch above the water surface. The lever arm for the drag force was consequently very small compared to that for lift. Errors due to an incorrect estimate of the position of the lift force should also be small since the 6 foot lever arm is large compared to the dimensions of the model. In combination, these errors are believed to be less than 5%. The sensitivity of the spring-and-weight combination was such as to give a possible 0.05 lb. (or $C_L$ = 0.01) error for any lift determination. Errors in measuring the submergence at which the lift determinations were made are believed to be less than 0.1 diam. The slopes of the graphs indicate that 0.1 diam. uncertainty in submergence might produce about 0.025 error in lift coefficient. Errors due to velocity measurement and to deviations from uniform velocity profile near the surface are small. The accuracy of the lift coefficients are consequently believed to be within ± (5% of the reading +0.04). Check readings as well as the smoothness of the curves indicate that the precision is considerably better. These figures represent errors of measurement; they do not relate to deviation from exact similarity between model and prototype as discussed in the body of this report.

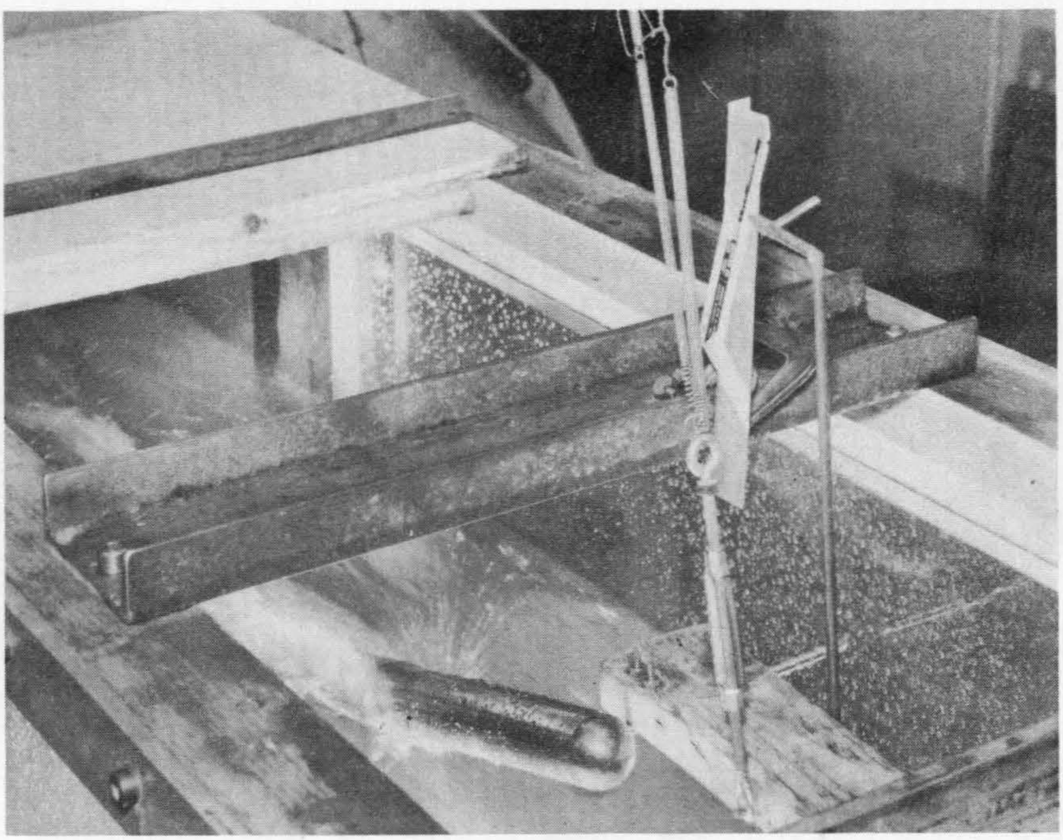

FIG. 8 – THE AFTERBODY OF A MODEL IN CONTACT WITH A FLOWING STREAM OF WATER.

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